Thermal Behavior of Energy-Efficient Substation Connectors

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***Abstract*— The contact resistance is the key variable that characterizes the stable performance and long-term service of an electrical connection. It is worth noting that the contact resistance in substation connectors can be several times that of the connector's resistance. To reduce connection losses and thus decrease connector's operating temperature, it is important to minimize contact resistance. The aim of this work is to characterize the relationship between the surface preparation, the resulting contact resistance and the thermal performance of substation connectors. First, the thermal behavior of substation connectors assembled with the traditional and a new installation method proposed by the authors has been characterized. It has been done by means of experimental temperature rise test and current cycle test. Thanks to these results, it has been proved that the new installation procedure allows reducing connector's temperature in operating conditions as well as the variability of the electrical resistance among different samples due to thermal stress. Moreover, by means of experimental measurements, the temperature dependence of the contact resistance has been analyzed, with the objective to characterize the performance of an electrical contact under different operating temperatures. To determine the temperature coefficient of the contact resistance, an experimental resistance measurement has been continuously performed during the cooling of a contact interface, previously heated at 200 ºC. This value can be very useful for an optimal design of the substation connectors.**

Keywords—contact resistance; substation connectors; surface preparation; thermal behavior; temperature rise; thermal cycle, temperature coefficient of resistance.

I. INTRODUCTION

In the last years there has been a considerable increase in energy consumption, especially in densely populated areas. This phenomenon has caused the risk of line saturation in some areas and the consequent need to increase power lines capacity. However, it is often extremely difficult to build new distribution and transmission lines, particularly in urban areas or in regions of ecological interest [1]. An important solution that emerged in the last years, due to its technological and economic viability, is the replacement of conventional conductors with HTLS (High-Temperature Low-Sag) conductors. HTLS conductors, with an almost identical section of conventional ones, allow increasing the nominal current capacity [2], with an allowable increase in operating temperature. However, the increase of power lines capacity imposes more severe operating conditions on devices such as substation connectors, involved in transmission and distribution systems, which are subjected to higher loads and have to operate at higher temperatures.

Substation connectors are the joints that physically link the power transmission line and the substation conductors and bus bars. Substation connectors, which will be considered in this paper, are aluminum alloy devices of mechanical type. This means that the coupling parts, i.e. the parts which transmit electrical power, are mechanically joined by means of bolts through applying a specific torque, with the aim to maintain the connection integrity and ensure an adequate contact resistance between connector and conductor. The contact resistance defines the energy-efficiency, the stable performance and the long-term service of an electrical connection. If contact resistance is low and stable in time, a good electrical connection and a long-term performance of substation connector is guaranteed; whereas, if it is high and unstable in time, it could cause overheating of the connector and, consequently, a reduced operating life [3].

Substation connectors are usually considered the weakest points in the power grid, mainly due to the poor installation practice and the lack of knowledge of their degradation rate [4]. These facts often involve the difficulty to predict the useful life of a component. Moreover, it is worth mentioning that the mechanical, metallurgical, thermal and electrical processes involved in the establishment and the maintenance of the electrical contact are very complex and nowadays there is a lack of a unified model which describes the phenomena that occurs at contact interface [4]. With the advent of HTLS conductors the role of the substation connectors in the transmission and distribution system is even more critical, because high temperature operation of conductors increases the current density and operating temperature of associated connectors. As a consequence, aging process of connectors is accelerated, and thus its expected service life reduced. Temperature cycling tests (at 125 ºC and 150 ºC) conducted on connectors that were originally rated for 70 ºC operating temperature have detected the electrical and thermal deterioration in most types of connectors [5]. Thus, if HTLS cables will replace traditional conductors, the installed population of connectors will age more rapidly and the number of connector failures will increase due to the increased aging effects of higher temperature and current density.

Hence the need to characterize the thermal behavior of an electrical contact and optimizing the installation procedure of substation connectors in order to reduce contact resistance and ensure a lower temperature during normal operating conditions. Contact surface preparation is essential to guarantee proper contact between connector and conductor since the contact resistance can notably degrade substation connectors' performance. In technical literature the most commons installation procedures for aluminum-to-aluminum and aluminum-to-copper connections and their performances under thermal cycling are analyzed and compared [6][7][8][9][10]. Most of these works, have shown that the mechanical abrasion (reached by brushing surfaces) and lubrication through contact aid compound application is the most efficient method to ensure an adequate contact resistance in aluminum-to-aluminum connections [4]. However, this practice can be further improved in a simple way. In a previous work [11] the authors proposed a new chemical cleaning method for substation connectors to minimize contact resistance. Results presented showed that the proposed installation procedure allows minimizing the contact resistance of substation connectors, and thus improving energy efficiency of the electrical connection.

The aim of this work is to characterize the relationship between installation procedure, the resulting contact resistance and the thermal performance of substation connectors. First of all thermal behavior of substation connectors assembled with the traditional [12] and the new installation method proposed by the authors [11] will be characterized by means of experimental Temperature Rise test according to the ANSI/NEMA CC1-2009 standard [13] and Current Cycle test according to ANSI C119.4-2011 standard [14]. Thanks to these results, the temperature and the variation of contact resistance due to thermal stress, with the two installation methods, will be analyzed and compared. Moreover, by means of experimental measurements, the temperature dependence of contact resistance will be analyzed, with the aim to characterize the performance of an electrical contact at high operating temperatures. To determine the temperature coefficients of contact resistance, an experimental resistance measurement will be performed continuously during the cooling of a contact interface, previously heated at 200 ºC.

II. ANALYZED SUBSTATION CONNECTORS AND INSTALLATION PROCEDURES

A. Substation Connectors

Experimental temperature rise and current cycle tests have been conducted on a loop composed by two different typologies of substation connectors from SBI Connectors catalogue and 32 mm diameter AAAC conductors. Specifically, the analyzed connectors are listed below:

- T-connector S330TLS (a);
- Coupler with two caps S330SLS (b);

An experimental test to characterize temperature dependence of contact resistance has been conducted on a smaller loop composed by a S330SLS connector, which joined two 32 mm diameter AAAC conductors.

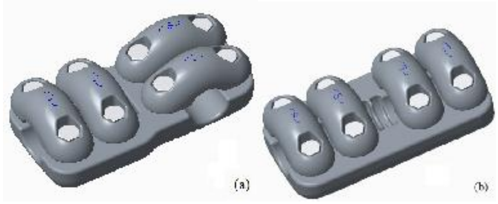

Figure 1. The substation connectors analyzed. a) S330TLS t-type connector. b) S330SLS coupler connector.

B. Installation Procedures

Different assembling procedures and surface treatments are analyzed and shown through Table I.

TABLE I. INSTALLATION PROCEDURES APPLIED TO SUBSTATION CONNECTORS.

Installation Procedure	Surface's Treatments	
	AAAC Conductor	*Substation Connector*
1	• Brushed • Oxide inhibiting compound application	• Brushed • Oxide inhibiting compound application
2	• Brushed • Oxide inhibiting compound application	• **Chemical cleaning** • Oxide inhibiting compound application

The conventional assembling procedure, indicated as procedure No. 1 consists of brushing both conductor and connector's surfaces just before assembling, with the aim to remove the aluminum oxide film. After brushing it is generally recommended to apply an oxide inhibiting compound on both contact surfaces. These compounds ensure good contact and enhance the expected life of the connection [12].

The chemical cleaning treatment, provided for procedure No. 2, involves the application of a chemical solution on the contact surfaces between the connector and the conductor during about 25 minutes, after which the components are assembled according to the standard procedure [11].

III. EXPERIMENTAL SETUP

A. Test 1: Experimental temperature rise test according to the ANSI/NEMA CC1 standard

The temperature rise test is useful to determine the substation connector's thermal behavior under both transient and steady state condition and thus to evaluate if its design and installation procedure are compatible with the electromagnetic-thermal stress at which it is subjected. The temperature rise is determined at 100, 125, and 150% of the rated current, with equilibrium temperatures obtained at each level. The standard describes equilibrium temperature as a constant temperature (+/-2 ºC) between three successive measurements taken five minutes apart. The rated current shall be in accordance with tabulated values that establish this value as function of conductor size.

A temperature rise test according to the requirements of the NEMA CC1-2009 [13] was conducted in the AMBER-UPC laboratory. The test object was a closed loop circuit composed of eight connectors, as shown in Fig. 2. The elements that composed the loop were four S210ZTLST-connectors, four S210ZA4P23LS terminals and an AAAC SALCA 593 conductor with diameter d = 32 mm. The two t-connectors were used with the sole purpose of connecting the loop to the power transformer, thus they were not taken into account for this analysis. Three connectors were installed with the procedure nº 1, as shown in Fig. 2. Whereas the remaining connectors were installed by applying procedure No. 2, with the purpose of comparing the thermal behavior of connectors assembled with the different procedures. The experimental test was performed at atmospheric conditions (18 ºC). Current values settled during the test are shown in Table II.

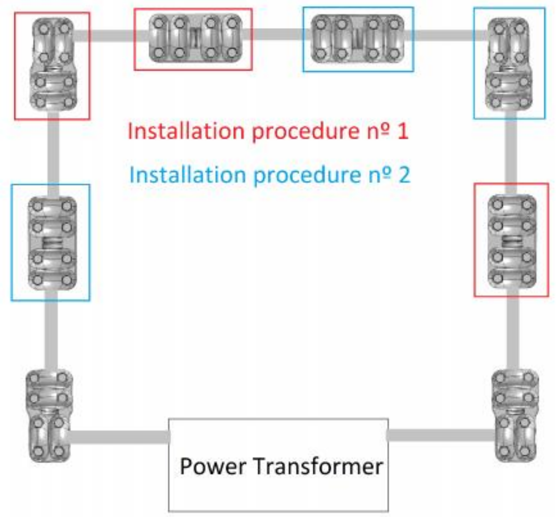

Figure 2. Experimental temperature rise test. Testing loop with connectors with different installation procedures. Connectors assembled with procedure No. 1 are indicated in red, whereas connectors installed with procedure No. 2 in blue..

TABLE II. CURRENT VALUES SETTLED DURING THE TEMPERATURE RISE TEST.

Step	Testing current	
	% of nominal current	*Value [A_{RMS}]*
1	100 %	1015
2	125 %	1270
3	150%	1525

The experimental setup consists of a single-phase variable autotransformer connected in series with a single-phase transformer (120 kVA, 0-10 kA, 50 Hz). They are connected to the test loop, which includes the eight connectors described above. A calibrated Rogowski coil probe (Fluke i6000s Flex) was employed to measure the output current provided by the transformer at each current level. Current measurements have an uncertainty of about 2%.

To measure the temperature evolution during the transient phase and in steady state condition, 16 K-type thermocouples with an AISI 316 external sheath of 1 mm diameter were placed on the connectors' bodies and on the top points of two AAAC conductors. A small hole was drilled through the connector body, to ensure the contact of the thermocouple with the connector surface. The thermocouples were connected to an acquisition card and the signal was processed by a PC. Measures were acquired every 10 seconds.

B. Test 2: Experimental Current Cycle test according to the ANSI C119.4 standard

Connector's behavior can also be evaluated by means of the standard current cycle test regulated by the ANSI C119.4-2011 standard [14]. The current cycle test is a very important tool to evaluate the aging process of connectors. Thermal cycles result in thermal expansion and contraction of the electrical contact interface, which contributes to degrading the contact points [4]. The test current must be adjusted to result in a steady-state temperature rise on the control conductor between 100°C and 105°C above ambient temperature.

Temperature measurements of the connectors, conductors, and ambient air have to be made at the end of the specified heating cycle, immediately before the current is turned off, whereas resistance measurements have been made at the end of the heating cycle period, with all connectors thermally stabilized at the room temperature. Fifteen thermal cycles according to the requirements of the ANSI C119.4-2011 standard were conducted in the AMBER-UPC laboratory. The test object and the experimental setup, shown in Fig. 3, were the same explained in the previous section. Experimental tests were performed at atmospheric conditions (15 ºC). An additional K-type thermocouple was used to measure the room temperature.

Figure 3. Heat-cycle test. Experimental setup.

C. Test 3: Determination of temperature dependence of contact resistance

With the aim to characterize the temperature dependence of the contact resistance in substation connectors, an experimental test was performed in AMBER/UPC laboratory. The contact interface between a substation connector and a conductor, assembled with procedure No. 2, has been heated at 300% of nominal current of conductor until reaching the equilibrium temperature. Then, the power transformer was switched off and disconnected from the testing loop. At this point, the contact resistance was measured continuatively during the cooling. The test object was a closed loop one connector, as shown in Fig. 4. The elements that composed the loop were a S330SLS connector and AAAC SALCA 593 conductor with diameter *d* = 32 mm. To measure the temperature of the test object, 4 T-type thermocouples were placed on the connector' body, on the top points of AAAC conductor and in the contact interfaces between connector and conductor.

Figure 4. Determination of the temperature dependence of contact resistance. Heating of the testing loop.

The Kelvin or 4-wire method was employed to perform continuous resistance measurements, as shown in Fig. 5. To this end a Raytech Micro-Centurion II digital micro-ohm meter (max. current 200 A_{DC}, accuracy ±0.01μΩ) was used. Resistance measurement was performed between points A and B as shown in Fig. 5. Simultaneously, was recorded the associated temperature through thermocouples.

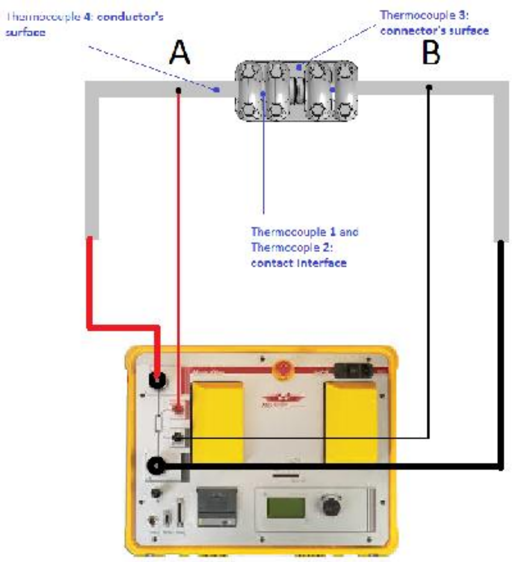

Figure 5. Resistance measurement with the 4-wires method and thermocouples' position.

The contact resistance is obtained by subtracting the resistance of the portion of the conductor and the resistance of the connector at the resistance measured between A and B. The theoretical resistance of the connector was calculated through electromagnetic FEM-simulation, while conductor resistance was obtained through experimental measurement.

IV. Results

A. Test 1: Experimental temperature rise test according to the ANSI/NEMA CC1 standard

The temperature rise test allows determining the substation connector's thermal behavior under both transient and steady state condition. The test has been performed at three current levels, as indicated in Table II. Fig. 6 shows the temperature rise for the three current levels, and the zoom of the third current step, that is at 150% of nominal current, for the six connector analyzed.

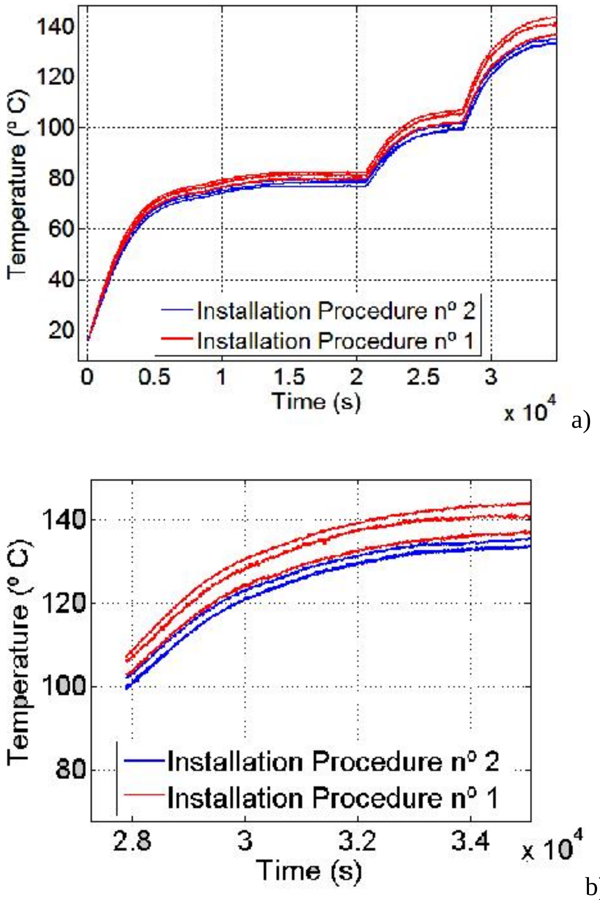

Figure 6. a) Results of the experimental temperature rise test. In red it is shown the temperature of the connectors installed with procedure No.1, while in blue connectors assembled with procedure No. 2. b) Zoom of the third step, performed at 150% of nominal current.

The test demonstrates a better thermal behavior of the connectors installed with procedure No. 2, showing a lower transient and steady-state temperature, compared to the temperature of connectors assembled with traditional procedure.

TABLE III. TEMPERATURE RISE TEST. STEADY STATE TEMPERATURES OF ANALYZED CONNECTORS, AT THE THIRD CURRENT STEP.

Connector			**Steady-state Temperature (ºC) at $I_3 = 1522\ A_{RMS}$**		
Type	Item	Inst. Procedure		***Mean***	***Std. Deviation***
T	3	**1**	141.4	140.8	3.4
Coupler	4		143.9		
Coupler	7		137.15		
Coupler	2	**2**	133.5	134.3	1.1
Coupler	5		133.8		
T	6		135.6		

Moreover it should be noted that, as summarized in Table III, with procedure No. 2 there is less variation of temperature between the three specimens analyzed with the same treatment. This behavior is very important to evaluate the stability and the reliability of a connector.

B. Test 2: Experimental current cycle test according to the ANSI C119.4 standard

As explained in the previous chapter, the current cycle test allows determining the thermal aging of substation connectors. Fifteen thermal cycles according to the requirements of the ANSI C119.4-2011 standard were conducted in the AMBER-UPC laboratory. Table IV shows the temperature measurements performed at the end of the last heating cycle, immediately before the current was turned off. Table V shows the connector's resistance, the contact resistance and its variation before and after the test.

The theoretical resistance of the connector was calculated through electromagnetic FEM-simulation, which was subtracted from the measured resistance, thus obtaining the contact resistance. Results summarized in Table IV show that connectors assembled with procedure No. 2 have a lower steady-state temperature, compared to the connectors assembled with the traditional procedure.

TABLE IV. HEAT CYCLE TEST. STEADY STATE TEMPERATURES OF ANALYZED CONNECTORS. CYCLE NO. 15.

Connector			**Steady-state Temperature (ºC)**
Type	Item	Inst. Procedure	***Cycle 15***
T	3	**1**	86.3
Coupler	4		88.5
Coupler	7		84.0
T	2	**2**	81.4
Coupler	5		80.6
Coupler	6		82.6

Moreover, observing results summarized in Table V, the the contact resistance variation of the connectors assembled with procedure No. 1 is high and instable. Conversely, the contact resistance variation for the connectors assembled with procedure No. 2 is lower and stable for both analyzed geometries.

TABLE V. HEAT CYCLE TEST.RESISTANCE MEASUREMENTS OF ANALYZED CONNECTORS BEFOR AND AFTER THERMAL CYCLES.

Connector			**Connector Rasistance (µΩ)**		**Contact Resistance (µΩ)**		
Type	Item	Inst. Proc.	***Before (Cycle 0)***	***After (Cycle 15)***	***Before (Cycle 0)***	***After (Cycle 15)***	*Var*
T	3	**1**	9.14	9.84	4.22	4.96	+17.5%
Coupler	4		11.3	12.04	7.00	7.77	+11%
Coupler	7		9.40	8.78	5.10	4.51	-11.6%
Coupler	2	**2**	6.78	6.82	2.48	2.55	+2.8 %
Coupler	5		6.80	6.70	2.50	2.43	+2.8 %
T	6		9.60	9.45	4.68	4.57	+2.3 %

C. Test 3: Determination of the temperature dependence of the contact resistance

The contact interface between a substation connector and a conductor, assembled with procedure No. 2, has been heated at 300% of nominal current, reaching an equilibrium temperature of 200º C. During the cooling, the resistance between points A and B, and the temperature of the test objects were measured continuously.

The contact resistance has been calculated as:

$$R_C(T) = R_{A-B}(T) - R_{Conn}(T) - R_{Cond}(T) \qquad (1)$$

where R_c is the contact resistance, $R_{A\text{-}B}$ the resistance measured between points A and B, R_{Conn} the resistance of the connector calculated by means of FEM simulation and R_{Cond} the conductor's resistance, determined by means of experimental measurements.

Conductor's and connector's resistance are assumed to be temperature dependent:

$$R_{Cond}(T_{Cond}) = R_{0,Cond} \cdot (1 + \alpha_{Cond}(T_{Cond} - T_{0,Cond})) \qquad (2)$$

$$R_{Conn}(T_{Conn}) = R_{0,Conn} \cdot (1 + \alpha_{Conn}(T_{Conn} - T_{0,Conn})) \qquad (3)$$

where T_{cond} and T_{Conn} are the temperature of the conductor and connector's surfaces measured by means of T-type thermocouples, R_0 the resistance at reference temperature (T_0 = 293.15 K) and α is the temperature coefficient.

Fig. 7 shows the contact resistance as function of the contact interface temperature.

From the analysis of the collected data, it can be concluded that the contact resistance has an almost linear behavior between room temperature and 200 °C. Through the linear fit a temperature coefficient α = 0.0055 ºC^{-1} is obtained.

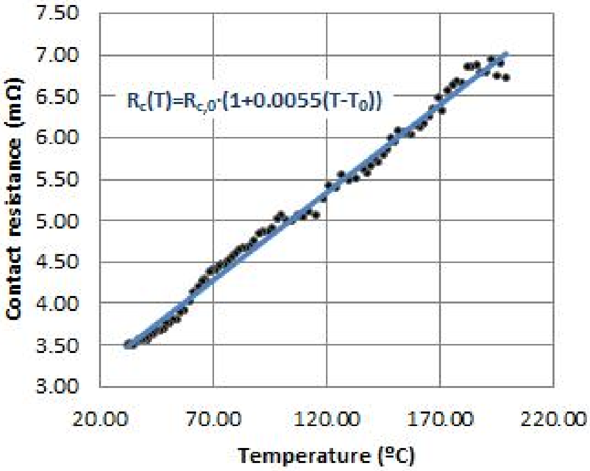

Figure 7. Contact resistance as a function of the contact interface temperature. Measured values and linear approximation.

V. CONCLUSIONS

HTLS conductors, with an almost identical section that that of the conventional ones, allow increasing the nominal current capacity [2], with an allowable increase in operating temperature. However, the increase of power lines capacity imposes more severe operating conditions on devices such as substation connectors, involved in transmission and distribution systems, which are subjected to higher loads and have to operate at higher temperatures. Hence the need to characterize the thermal behavior of an electrical contact and optimize the installation procedure of substation connectors in order to reduce contact resistance and ensure a lower temperature in operating conditions. In this work, the thermal behavior of substation connectors assembled with the traditional and a new installation method proposed by the authors has been characterized by means of the experimental temperature rise and current cycle tests. It has been demonstrated that the new installation procedure (No. 2) allows reducing connector's temperature in operating conditions and the resistance variability among different samples due to thermal stress. Thus, it has been demonstrated that, through the new installation procedure, the thermal behavior of substation connectors is more stable and reliable. Moreover, the temperature dependence of the contact resistance has been found out, with the objective to characterize the performance of an electrical contact at different operating temperatures. A global temperature coefficient of the contact resistance from room temperature to 200 ºC α = 0.0055 ºC^{-1} has been found, which can be useful for an optimal design of the substation connectors.

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